South Carolina Association of
Municipal Power Systems

Stray Voltage Analysis

August 10, 2015

J. TED ORRELL, PE, PARTNER

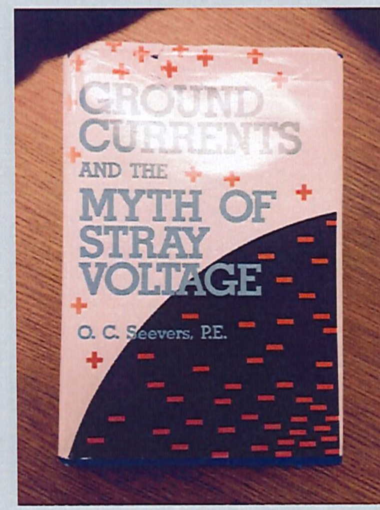
UTILITY TECHNOLOGY
ENGINEERS-CONSULTANTS

UTEC

What is "Stray Voltage"?

A very good reference on the subject is:

"Ground Currents and the Myth of Stray Voltage" by O. C. Seevers, P.E. Mr. Seevers' book focuses on stray voltages in dairy farms, but the principles addressed apply to any stray voltage situation.



In chapter 1, Mr. Seevers makes several important comments and observations:

- Stray voltage is "voltage which appeared where it had no business being".
- Nowhere has anyone looked at the distribution system and analyzed how it works. How primary neutral current returns to its source."

Is Stray Voltage a Problem?

At a minimum, stray voltage can be annoying. At a maximum, stray voltage can be lethal.

Has anyone in the audience had to deal with and resolve a Stray Voltage problem?

Definition of Stray Voltage

One definition I found is:

"Stray voltage (SV) is a special case of neutral to earth voltage (NEV) which is the voltage measured between the electrical system neutral conductor and anything connected to the earth. NEV exists on all grounded electrical systems and is the result of neutral return current flowing in the earth. Theoretically, approximately 1/3 of the return current in a multi-grounded wye connected system returns to the source through the earth "ground" path. Thus, stray voltage, in reality, is caused by stray current. When this stray current creates a voltage between two points that can be contacted by a human or animal, and is above the threshold of perceptibility, it is referred to as "stray" voltage.

Due to the common grounding of the Utility System and the Customer electrical system, any NEV on the utility system will be transferred to any grounded objects in a building including metal water pipes. If this NEV/SV exceeds "Levels of Concern", it generally occurs when there is something that needs to be corrected either on the utility system or the customer wiring system.

Definition of Stray Voltage

A second definition I found is:

"**Stray voltage** is the occurrence of electrical potential between two objects that ideally should not have any voltage difference between them. Small voltages often exist between two grounded objects in separate locations due to normal current flow in the power system. Large voltages can appear on the enclosures of electrical equipment due to a fault in the electrical power system, such as a failure of insulation."

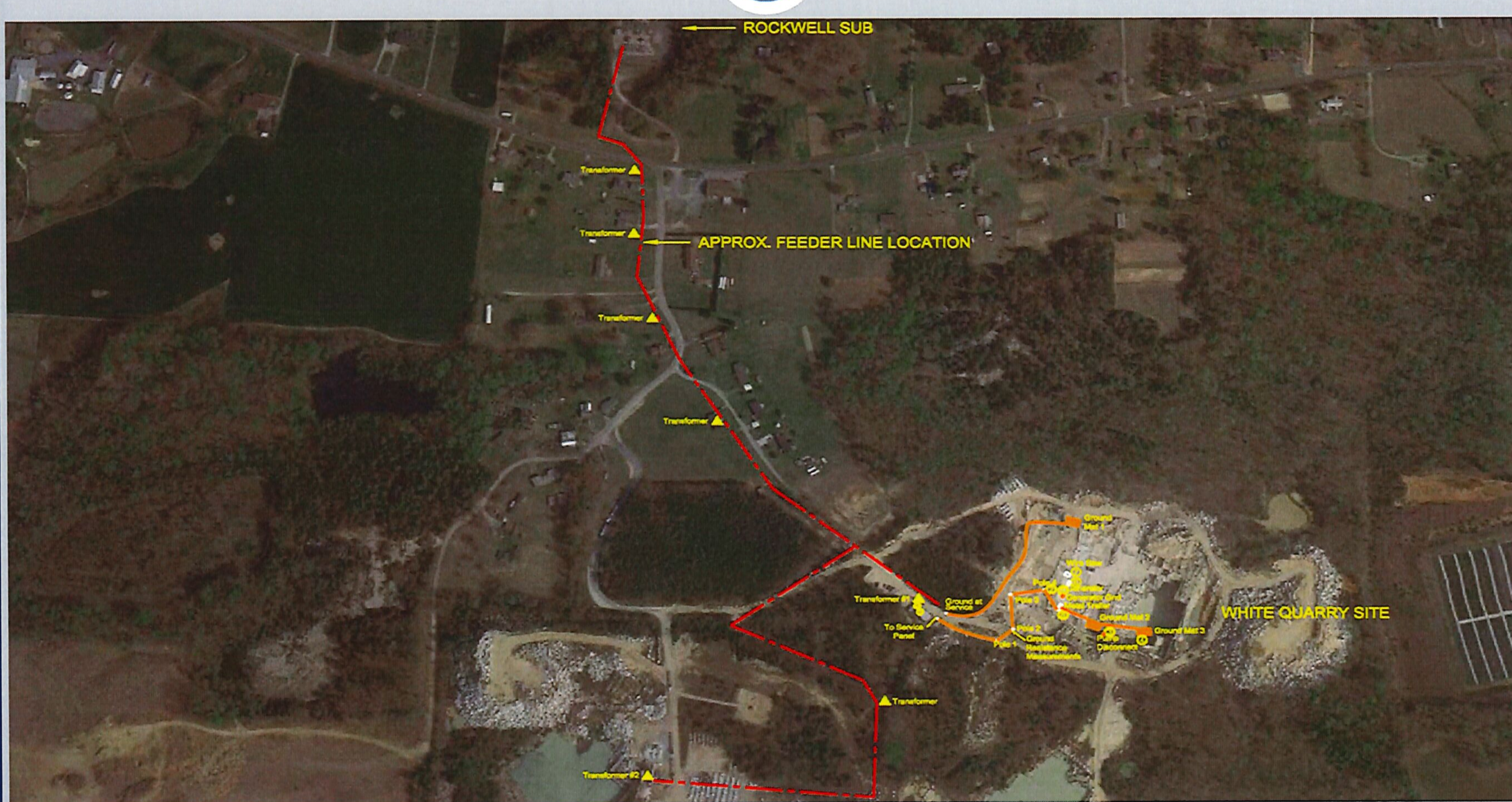
Examples of Stray Voltage

1. Shock when in a swimming pool and touching the metal ladder to get out of the pool
2. Shock when touching a pole down guy wire
3. Shock to cattle when attached to a milking machine or feeding
4. Shock when touching grounded equipment in a rock quarry

TODAY WE ARE GOING TO DISCUSS

A recent UTEC investigation in which equipment operators working in a rock quarry received shocks when touching grounded equipment."

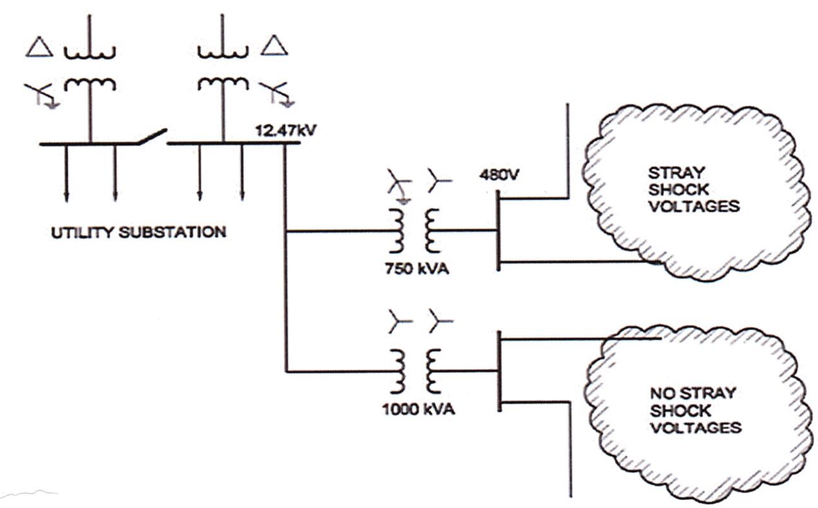
Aerial View of Project and Electrical Lines



South Carolina Association of Municipal Power Systems

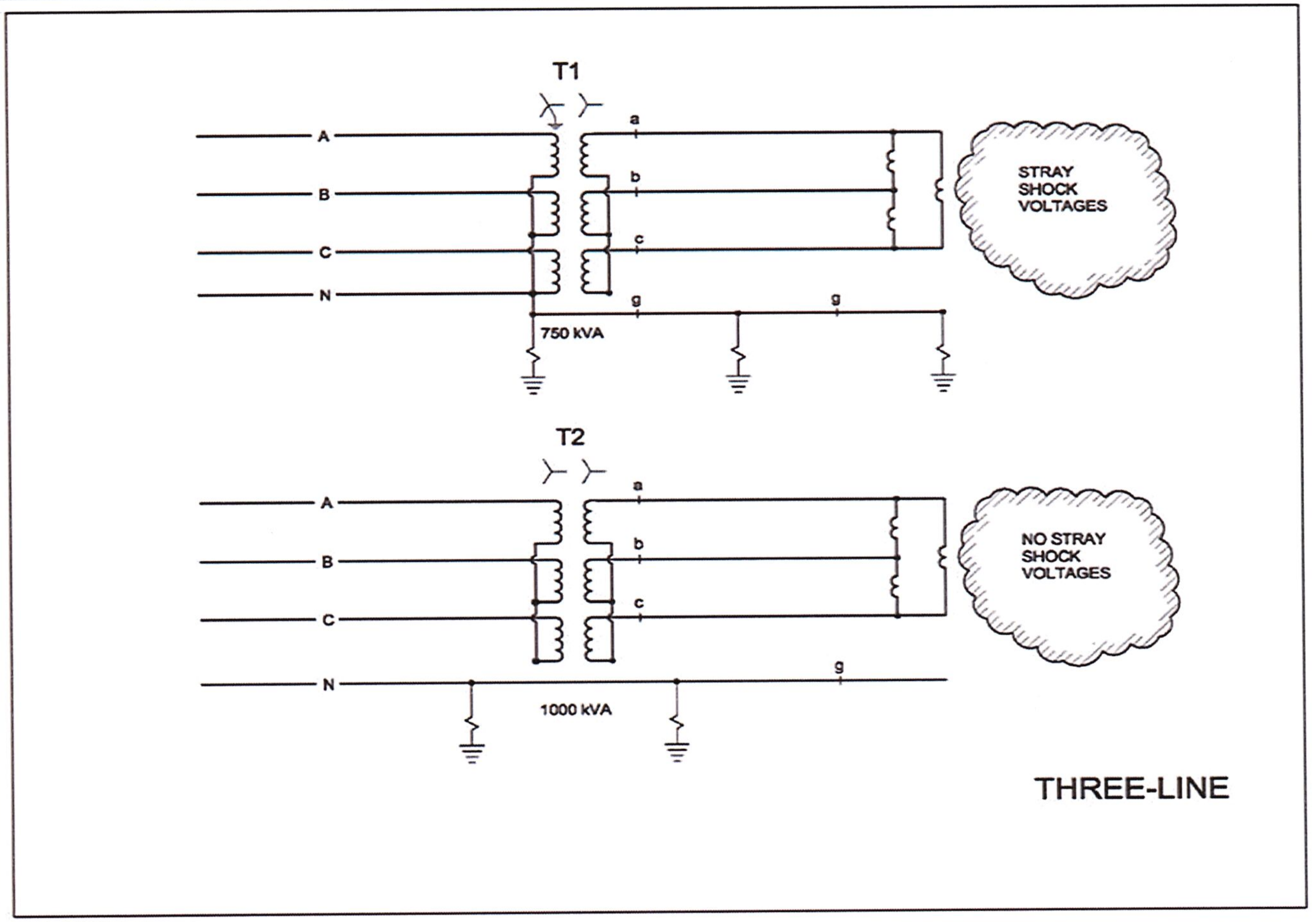
UTEC

Electric System One-Line



UTEC

Electric System Three-Line



Power Supply Utility Substation Loads

The Power Supply Utility serves five primary distribution circuits from the substation that feeds the quarry. Three of the primary feeders are well balanced among phases. Two of the primary feeders are not well balanced. Following are the typical currents for the two unbalanced phases::

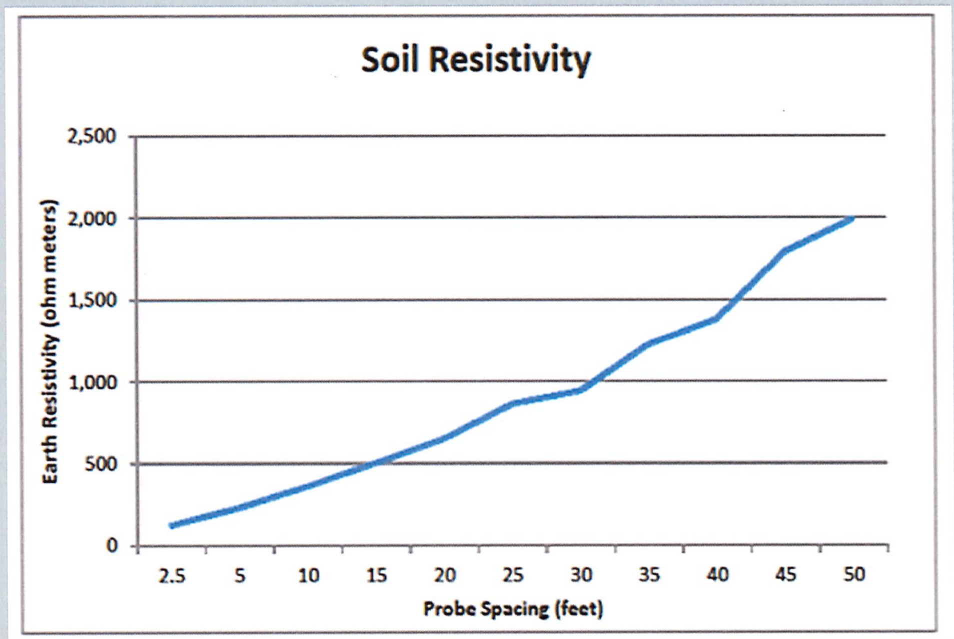
Unbalanced Primary Distribution Circuits	Ph. A amps	Ph. B amps	Ph. C amps
Circuit 1	117	179	86
Circuit 2	160	115	63
Total unbalanced Current	277	294	149

Assuming 120° phase rotation separation among the three phases, the total neutral/ground current resulting from the unbalanced currents is 137 amps at -66 degrees. This neutral/ground current will produce surface voltage profile along the ground for the multi-grounded distribution system served from the substation.

Soil Resistivity Analysis

UTEC performed a set of Soil Resistivity tests on site. UTEC also used its SAFE Engineering software to determine the equivalent 2-layer soil model.

- 71.7 ohm-meters for a depth of 2.5 feet
- 10,870.5 ohm-meters infinitely deep below 2.5 feet

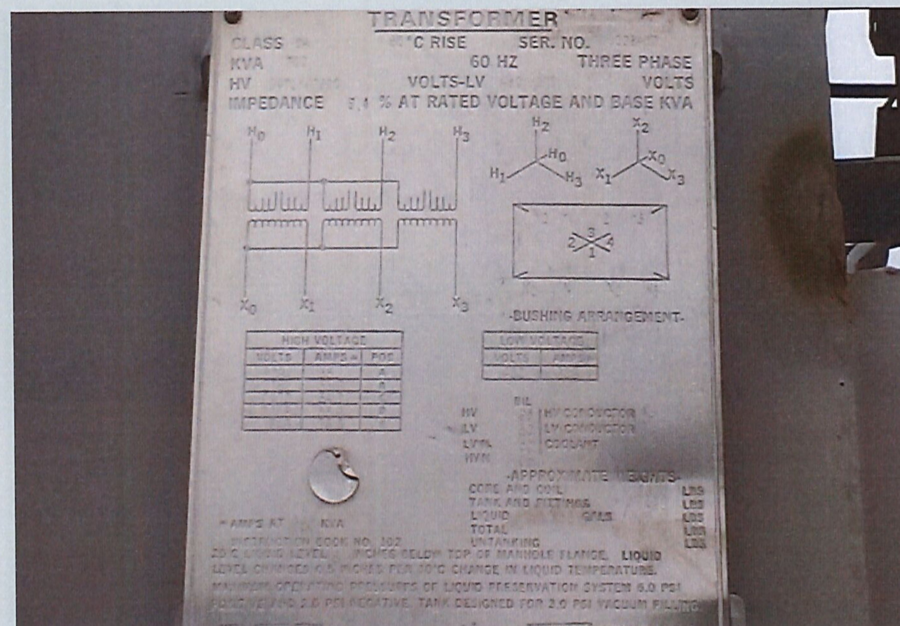


UTEC

Photographs

T1

T1 nameplate



UTEC

Photographs

T1 services

ROA grounding

Photographs

3-phase flexible cables to quarry

Observations:

1. Two 3-phase delivery, or service, points
   - **Service Point 1**
     - 750 kVA, 12.47 / 7.2 kV **grounded wye** to 277/480 ungrounded wye transformer
     - Quadriplex messenger cable connected to power utility primary neutral and to a pre-fab metal building on customer end.
     - Customer has two ground rods installed outside its building conductor brought into metal enclosure attached to the metal building
     - The metal building provided a metallic connection between the power utility primary neutral and the customer ground
     - Customer service into the quarry uses flexible 3-phase cables with no. 6 insulated ground conductor, extending 1000 to 1500 feet from the service ground
     - Customer ground conductor connected to equipment frames
     - Operating personnel would frequently be shocked in the quarry when touching metallic structures
     - UTEC measured as much as 21 volts from the ground conductor in the quarry and a probe stuck in the ground adjacent to equipment

Observations: Continued

- **Service Point 2**
  - 1000 kVA, 12.47 / 7.2 kV **ungrounded** wye to 277/480 ungrounded wye transformer
  - Quadriplex messenger cable connected to power utility neutral and on customer end connected to customer service panel ground bus and customer ground rod
  - No reported shock voltages in service point 2 area

Possible Causes of the Stray Voltage Investigated

1. Faulty Customer 600 Volt Cables
2. Longitudinal Magnetically Induced Voltage in Insulated Ground Conductor
3. Electric Field Capacitive Induced Voltage in Ground Conductor
4. Power Utility Neutral Voltage from Transformer Charging Current
5. Power Utility Neutral Voltage from 60 Hz Single-Phase Load Current
6. High resistance or open point in Power Utility Primary Neutral Conductor
7. Stray Ground Currents from Outside Source

Computer Model / Analysis Results

Two options to model the circuit: Loop Equations and Nodal Equations

UTEC chose nodal equations. Each neutral span is modeled using the classical Carson and Campbell equations for line impedance with earth return.

For a deep soil resistivity of 10,000 ohm-meters, the effective depth of return is:

- Fundamental Frequency (60 Hz) – 5.28 miles
- 3rd Harmonic Frequency (180 Hz) – 3.05 miles

The Nodal Model is as follows:

Computer Model / Analysis Results

Nodal Model

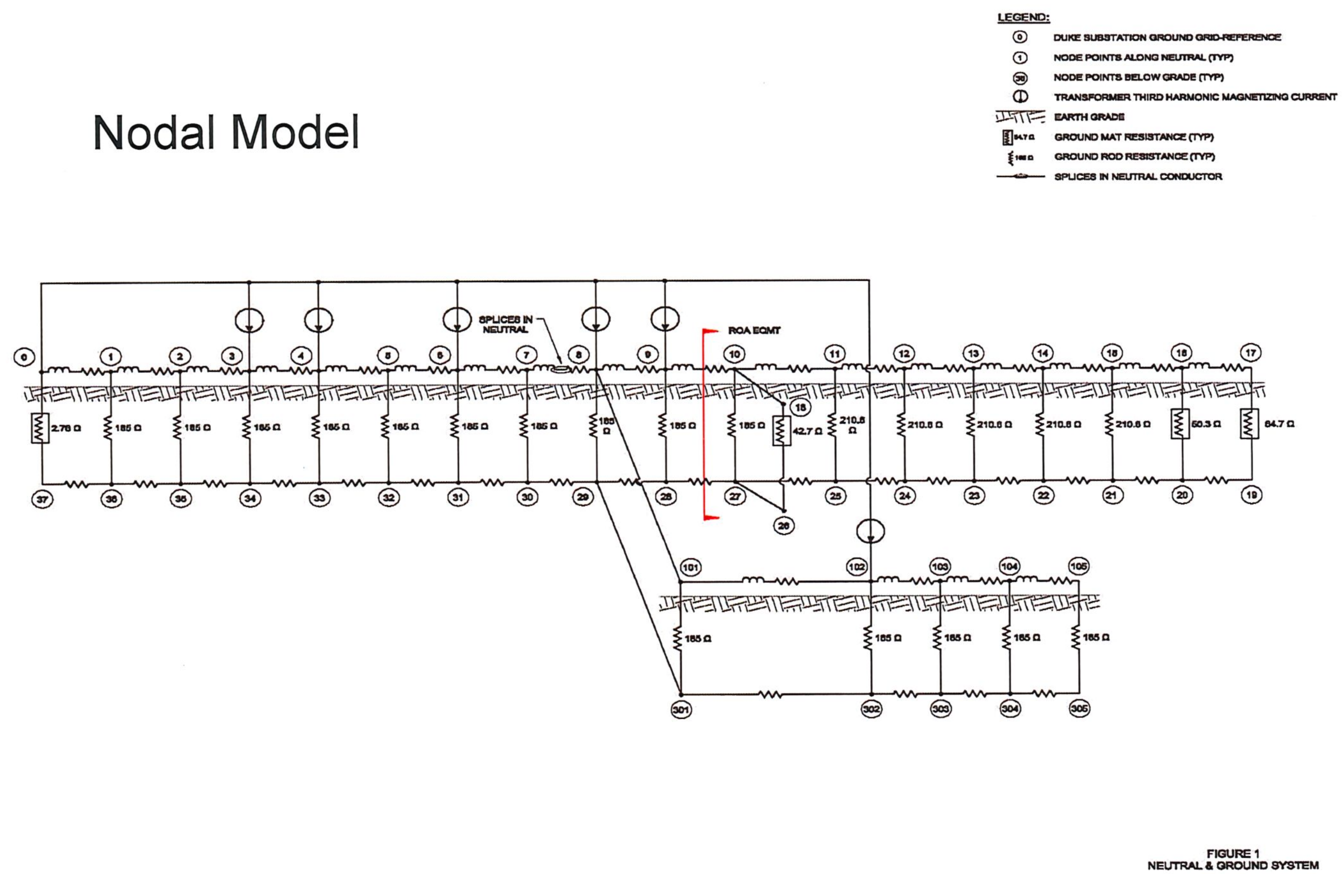


FIGURE 1
NEUTRAL & GROUND SYSTEM

UTEC

Mitigation Modifications and Results

Power Utility modified its service conductor connections to the metal building, insulating the messenger from the building and thus separating the utility neutral from the quarry ground system.

UTEC made voltage measurements between the quarry ground system conductor and a disconnect switch support structure 1500 feet away from the T1 service before and after the modification as follows.

- Before modification – 21 V RMS
- After modification – 10.9 V RMS

The modification reduced the stray voltage by about 50%.

The next question was, "What is causing the remaining 10.9 volts of surface voltage?

There are several possible reasons for the remaining voltage as follows:

1. Mutual surface potential resulting from the 3rd harmonic portion of the charging current for T1 flowing into the T1 ground
2. Power utility neutral/ground current in the tap serving the quarry resulting from high resistance in one or all of three different identified neutral conductor splices
3. Overall power utility neutral voltage to remote earth resulting from the large phase imbalance of the two utility distribution circuits
4. Stray Ground Currents from "Outside Sources"

Mitigation Modifications and Results

Continued

We performed additional field tests that eliminated possible reasons 1 and 2.

The power utility re-balanced the two unbalanced circuits. Voltage measurements at the same disconnect switch support structure are shown below:

- Before rebalancing the circuits – 10.9 V RMS
- After modification – 6 V RMS

The rebalancing of other primary distribution circuits reduced the remaining surface voltage by about 55%.

We noted that the remaining 6 V was predominantly 3rd harmonic, or 180 Hz. This indicates that the remaining surface voltages are likely due to reason 4 above.

In this case, the "outside source" is probably the 3rd harmonic charging current for all transformers served by the substation, not just transformers served by the circuit to the quarry.

The soil resistivity in the service area of the utility substation is likely very high. Because of the high soil resistivity, the return 3rd harmonic ground currents are spread out and effectively return in a hypothetical conductor over 3 miles deep.

Conclusions

1. The modifications made to the T1 service, separating the utility neutral from the customer ground system, significantly reduced the measured surface voltages.
2. Significantly unbalanced phase currents in all circuits served by a solidly grounded substation transformer results in high neutral and ground currents. These ground currents flow back to the source substation through the large cross-section of the earth's volume and produce voltage potential as the currents flow.
3. High soil resistivity results in ground currents spreading out across the earth cross-section and being less concentrated near the surface of the earth in following the circuit back to the substation.
4. Balancing distribution circuits reduces surface potential

It may be difficult and nearly impossible to eliminate all surface voltages. However, for the magnitude of surface voltages remaining in the quarry for this project, no danger exists to humans.ns.

South Carolina Association of
Municipal Power Systems

QUESTIONS & DISCUSSION

August 10, 2015

J. TED ORRELL, PE, PARTNER
jtorrell@utilitytec.com

UTILITY TECHNOLOGY
ENGINEERS-CONSULTANTS

UTEC